Matched-Index-of-Refraction Flow Facility at Idaho National Laboratory

*Piyush Sabharwall, Donald M. McEligot, and Carl M. Stoots**
Idaho National Laboratory, Idaho Falls, Idaho 83415-3730

Abstract

The Matched-Index-of-Refraction Flow Facility at the Idaho National Laboratory has a unique capability to contribute to the development of validated computational fluid dynamics codes through the use of state-of-the-art optical measurement techniques, such as laser Doppler velocimetry, particle tracking velocimetry, and particle image velocimetry. The fluid/solid refractive index matching technique allows optical access in and around geometries that would otherwise be impossible, while the large test section of the Idaho National Laboratory system provides better spatial and temporal resolution than other matched-index-of-refraction facilities. Benchmark data for assessing computational fluid dynamics can be acquired for external flows, internal flows, and coupled internal/external flows for better understanding of physical phenomena of interest.

Introduction

The matched-index-of-refraction (MIR) flow system was modeled after a typical wind tunnel and was designed and fabricated by collaboration between scientists and engineers at Idaho National Laboratory (INL) and Universität Erlangen-Nürnberg.[1] The facility's key objectives are to understand fundamental physical phenomena better and to provide experimental data for assessment and validation of computational fluid dynamics and nuclear reactor system safety codes. The MIR facility permits non-intrusive velocity measurement (state-of-the-art) techniques—such as particle image velocimetry (PIV), particle tracking velocimetry (PTV), and laser Doppler velocimetry—through complex models/geometries without requiring probes and other instrumentation that could disturb the flow.[1,2] The large MIR system enables high spatial and temporal resolution. Optical refraction is a common phenomenon, often leading to distorted views. In this facility, the flow models are constructed from fused quartz and submersed in temperature-controlled mineral oil (the working fluid). Quartz and mineral oil have similar refractive indices (near room temperature); thus, the model optically disappears, making high-resolution optical measurement possible. Figure 1 demonstrates how refractive index-matching causes the quartz to disappear in the mineral oil.

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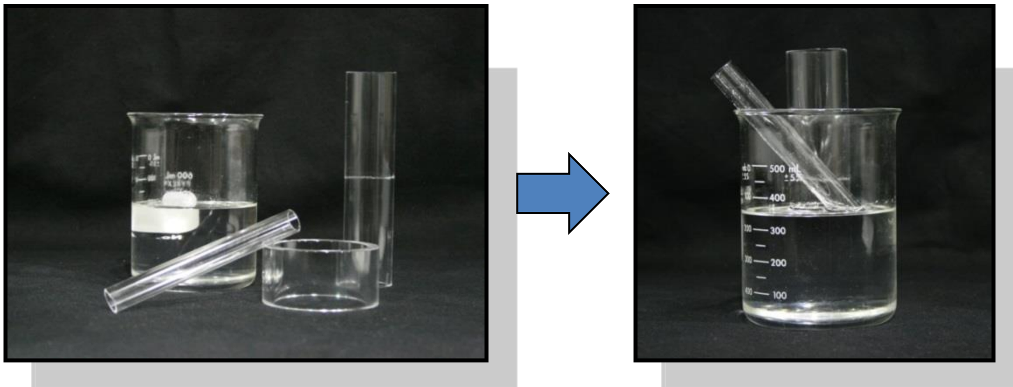
* Corresponding author: Carl Stoots, carl.stoots@inl.gov, 208-526-4527.

[1] Stoots, C., S. Becker, K. Condie, F. Durst, and D. McEligot, 2001, "A Large Scale Matched Index of Refraction Flow Facility for LDA Studies Around Complex Geometries," *Exp. in Fluids*, Vol. 30, pp. 391–398.

[2] Conder, T. E., 2012, "Particle Image Velocimetry Measurements in a Representative Gas Cooled Prismatic Reactor Core Model for the Estimation of Bypass Flow," *Doctoral Dissertation*, University of Idaho, IdahoFalls.



(a) (b)

Figure 1. Refractive index-matching of quartz and mineral oil: (a) quartz outside the oil and (b) quartz while submersed in the oil.

Description of the Facility

The MIR Facility was designed with an isothermal capability of sustaining a precise temperature in its test section. The facility consists of several components, including a settling chamber, square contraction, test section, and a separate auxiliary loop to provide independently controllable internal flow to installed models, as shown in Figure 2. The settling chamber is comprised of a single, stainless-steel honeycomb structure and several screens that straighten the flow, reduce turbulence, and remove non-uniformities. The 4:1 square contraction is attached downstream of the settling chamber and produces nearly uniform flow at the entrance of the test section. The test section is made from a polycarbonate material and contains large, optical glass windows to permit PIV and laser Doppler velocimetry measurements of the flow.[3] The large size of the test section provides high spatial resolution that makes it easier to obtain accurate data near the wall, which is not easy with smaller-scaled facilities.

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[3] McIlroy, H.M., 2011, “Matched Index-of-Refraction MH-GTR Prismatic Block Bypass Flow Control and Measurement Plan,” INL Internal Report, PLN-3669.

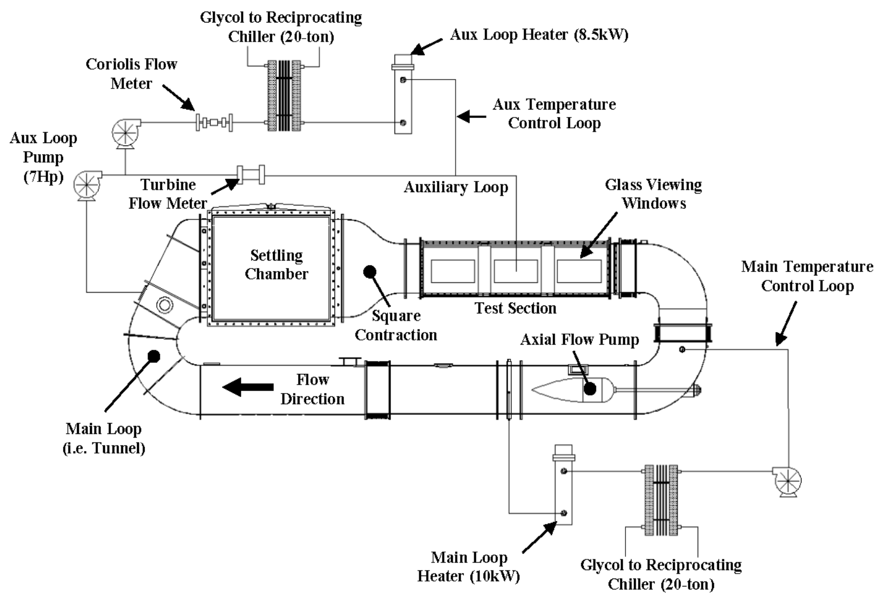

Figure 2. MIR Flow Facility.

The refractive index-matching temperature of the fluid is maintained within ±0.05°C of the prescribed index-matching temperature by an external control system. Table 1 displays the technical specifications of the MIR system.

Table 1. Technical specifications of the INL MIR system.

Characteristic	Specification
Test section cross section	0.61 m × 0.61 m (24 in. × 24 in.)
Test section length	2.44 m (8 ft)
Contraction ratio	4:1
Working fluid	Drakeol #5 light mineral oil
Index-matching temperature (°C)	Laser wavelength dependent
Mineral oil density	Matching temperature dependent
Refractive index of mineral oil and fused quartz	Matching temperature dependent
Mineral oil kinematic viscosity	Matching temperature dependent
Temperature control	External
Maximum inlet velocity	1.9 m/s (6.2 ft/s)
Inlet turbulence intensity	0.5%–15%

Measurement Technique and Uncertainty

Instantaneous velocity field measurements are primarily obtained with a stereo PIV system. Two charge-coupled device cameras are mounted on a three-directional traverse system that is controlled by three separate electric stepping motors. The PIV system uses double-pulsed, neodymium-doped yttrium aluminum garnet lasers that are usually mounted below the experiment model and produce vertical light sheets approximately 1–3 mm thick.[2] The three-directional traversing mechanism is mounted on rails parallel to the test section and is shown in Figure 3. This traversing system has a positional accuracy of ±2 μm (7.87×10^{-5} in).[2,3] Figure 3 shows the MIR flow system with the 3-D PIV system mounted on the three-directional traverse.

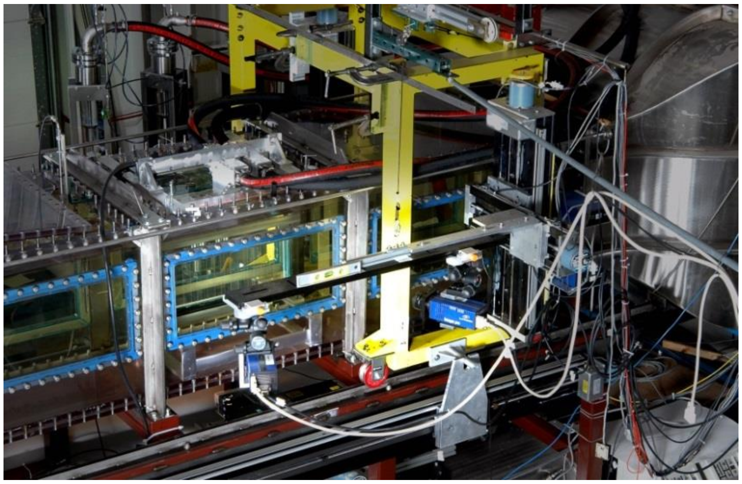

Figure 3. MIR flow system used to study fluid physics phenomena with a 3-D PIV system mounted on a three-directional traverse.

MIR results are typically in the form of three-component instantaneous and/or time-averaged velocities and Reynolds stresses. Two independent methods for computation of uncertainty from two-component PIV measurements are still being developed to quantify uncertainty and obtain accurate and reliable experimental data. These methods are the uncertainty surface method and the cross-correlation method (signal-to-noise ratio method). In the uncertainty surface method, an algorithm is tested to determine its response to various uncertainty contributors; in the cross-correlation method, the magnitude of the correlation peak is quantified to determine the uncertainty (INL/EXT-12-27728, INL report).[4]

Experimental Studies

Previous experiments performed in the MIR Facility focused on external flows (fluid flow over and around a body), internal flows (fluid flow inside of a body), and coupled internal/external flows, leading to the generation of experimental data for validation purposes and to better understanding of the physical phenomena of interest. Review of all of the previous studies and the current ongoing study is available at the MIR website (https://mir.inl.gov). Previous studies conducted in the MIR flow system include:

[4] Sabharwall, P., T. Conder, R. Skifton, C. Stoots, and E.S. Kim, 2013, "PIV Uncertainty Methodologies for CFD Code Validation at the MIR Facility," *INL External Report*, INL/EXT-12-27728, December 2013.

"Measurements of Fundamental Fluid Physics of Spent Nuclear Fuel Storage Canisters,"[5] "Transition Induced by a Square Rib,"[6] "Convective Processes in Spent Nuclear Fuel Canisters,"[7] "Fundamental Thermal Fluid Physics of High Temperature Flows in Advanced Reactor Systems,"[8] "Advanced Computational Thermal Fluid Physics (CTFP) and its Assessment for Light Water Reactors and Supercritical Reactors,"[9],[10] "The Boundary Layer Over Turbine Blade Models with Realistic Rough Surfaces,"[11] "Particle Image Velocimetry Measurements in a Representative Gas Cooled Prismatic Reactor Core Model For the Estimation of Bypass Flow,"[2] and "Criteria for Boundary Layer Transition."[12]

In one of the studies carried out in the MIR system that was focused on flows over the turbine blades,[11] McIlroy and Budwig made extensive boundary layer measurements over a flat, smooth plate model with non-dimensional parameters as on the front one-third of a first stage turbine blade from a high-pressure gas turbine engine and over the same model with an embedded strip of a realistic rough surface, as shown in Figure 4. The realistic rough surface was developed by scaling *actual* turbine blade surface data provided by the U.S. Air Force Research Laboratory by a factor of about 100, as shown in Figure 5. The boundary layer remained unstable (transitional) throughout the entire length of the test plate, and the rough patch caused the Reynolds shear stresses to increase in the region close the plate surface.

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5 Condie, K. G., G. E. McCreery, and D. M. McEligot, 2001, "Measurements of Fundamental Fluid Physics of SNF Storage Canisters," INEEL/EXT-01-01269, September 2001.

6 Becker, S., C. M. Stoots, K. G. Condie, F. Durst, and D. M. McEligot, 2002, "LDA-Measurements of Transitional Flows Induced by a Square Rib," *J. Fluids Engineering*, Vol. 124, pp. 108–117.

7 McCreery, G. E., K. G. Condie, R. L. Clarksean, and D. M. McEligot, 2002, "Convective Processes in Spent Nuclear Fuel Canisters," *Heat Transfer 2002 (Twelfth International Heat Transfer Conference)*, Grenoble, August, Vol. 4, pp. 663–668.

8 McCreery, G. E., T. D. Foust, D. M. McEligot, K. G. Condie, and R. J. Pink, 2002, "Measurements and Code Comparisons for Advanced Gas Reactor Coolant Channels Containing Spacer Ribs," Paper IMECE2002-33597, *ASME International Mechanical Engineering Congress*, New Orleans, November.

9 McEligot, D. M., J. Y. Yoo, J. S. Lee, L. E. Hochreiter, J. D. Jackson, S. O. Park, R. H. Pletcher, P. Vukoslavcevic, and J. M. Wallace, 2004, "Advanced Computational Thermal Studies and Their Assessment for Supercritical Reactors," *ANS 2004 Annual Meeting*, Pittsburgh, 13–17 June, *Trans., ANS*, Vol. 90, pp. 152–153.

10 McEligot, D. M., J. Y. Yoo, J. S. Lee, E. Laurien, S. O. Park, R. H. Pletcher, B. L. Smith, P. Vukoslavcevic, and J. M. Wallace, 2009. Advanced computational thermal studies and their assessment for supercritical-pressure reactors (SCRs). Proc., Supercritical CO_2 Power Cycle Symposium, Troy, 29–30 April.

11 McIlroy, H. M., and R. S. Budwig, 2007, "The Boundary Layer over Turbine Blade Models with Realistic Rough Surfaces," *J. Turbomachinery*, Vol. 129, pp. 318–330.

12 Becker, S., D. M. McEligot, E. J. Walsh, and E. Laurien, 2011, "Criteria for Boundary Layer Transition," ASME paper GT2011-45110, *International Gas Turbine Conf.*, Vancouver, June 2011.

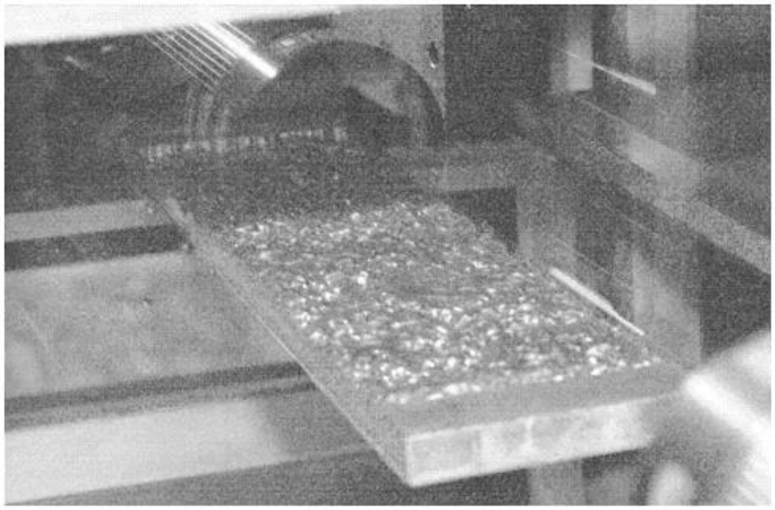

Figure 4. Quartz plate model with the rough patch shows the quartz is barely visible to the naked eye. [11]

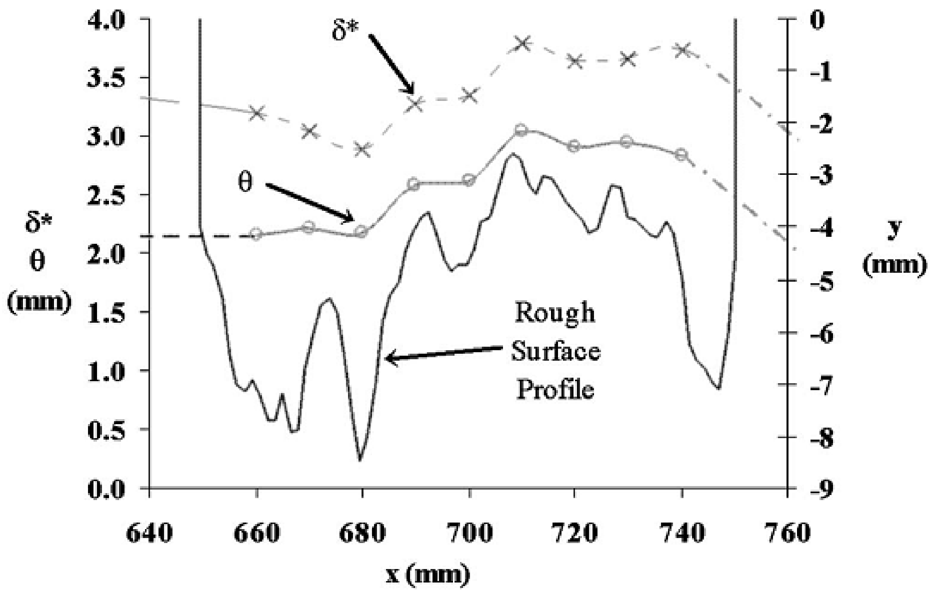

Figure 5. Displacement (δ∗) and momentum thicknesses (θ) increase over the rough patch (repesentative of turbine blade) with rough patch profile (right axis).[11]

As another example, a very high temperature nuclear reactor lower plenum study provided an extensive benchmark (~2Tb of data) for computational fluid dynamics code validation. A section of the lower plenum, which included four inlet jets from the simulated reactor above, was modeled of machined quartz, as shown in Figure 6. Two cameras slightly off angle from one another captured 3-D PIV data of various flow measurements at two Re_{jet} numbers (Re= 4,300 and Re = 12,400), as shown in Figure 6. The measured quantities included: streamwise-normal velocity, spanwise velocity, streamwise velocity (as shown in Figure 7), average turbulence intensity, and average turbulence kinetic energy. An example is shown in Figure 7; the quartz-to-mineral oil refraction index matching allowed for entire vector maps to be studied and recorded.

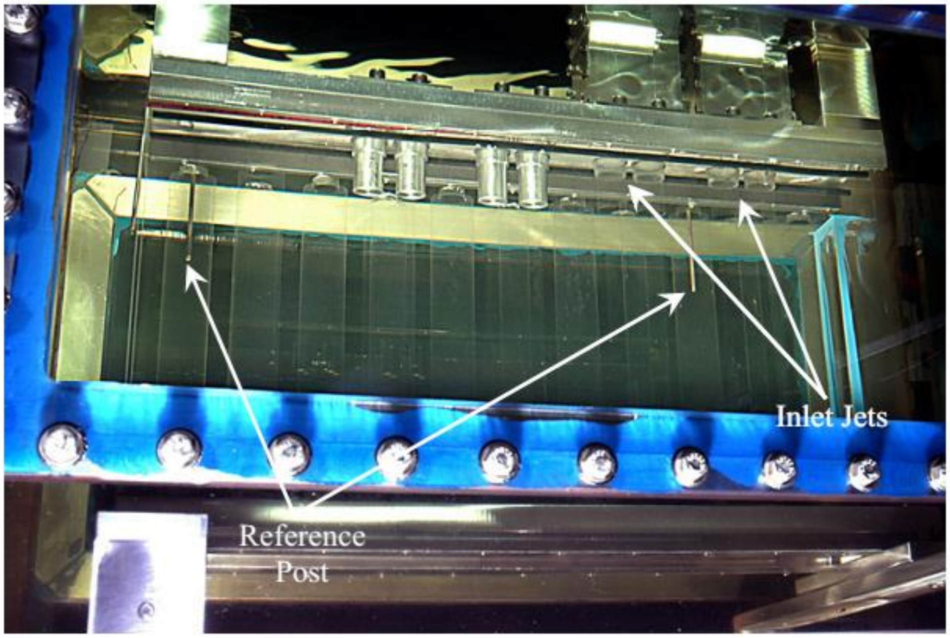

Figure 6. Quartz model of a very high temperature nuclear reactor lower plenum with inlet jets at the upper right.

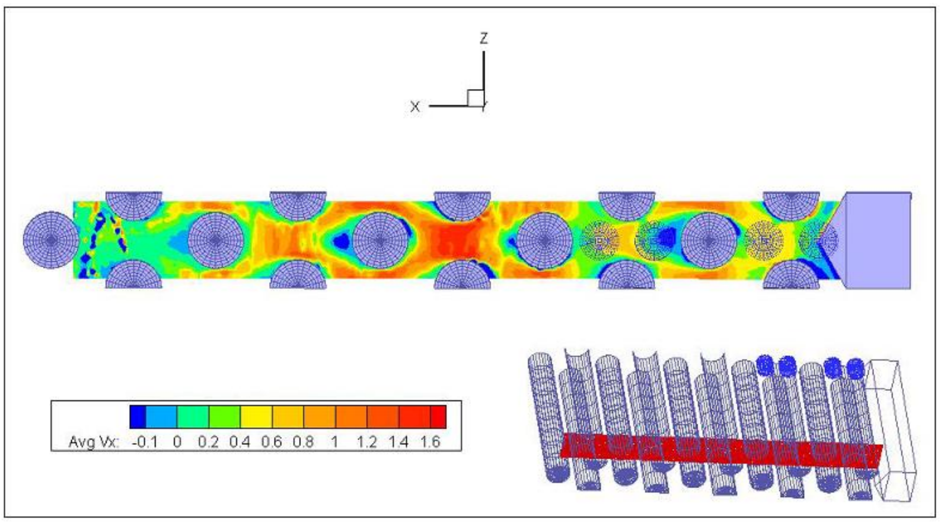

Figure 7. Mean streamwise velocity of a very high temperature nuclear reactor lower plenum at a horizontal slice at x = 160 mm from the top surface of the lower plenum (as shown on lower right).

Recent research conducted measurements of bypass transition with and without streamwise pressure gradients in the MIR test section.[13] The research examined three cases: (1) negligible pressure gradient with low freestream turbulence, (2) negligible pressure gradient with high freestream turbulence, and (3) adverse pressure gradient with high freestream turbulence (Figure 8). The end goal was to deduce entropy generation rates from PTV and PIV measurements. Employing a small field of view (FoV) with a telescoping camera provided instantaneous velocities by PTV computations in the near-wall region where entropy generation is concentrated. Further, this research developed data analysis procedures to deduce distributions of entropy generation rates from the instantaneous PTV results.[14,15] The boundary layer away from the wall used a larger FoV and reduced data with PIV software. Figure 9 demonstrates the high quality data obtained and its excellent spatial resolution in a resulting turbulent boundary layer downstream in the case with an adverse pressure gradient.

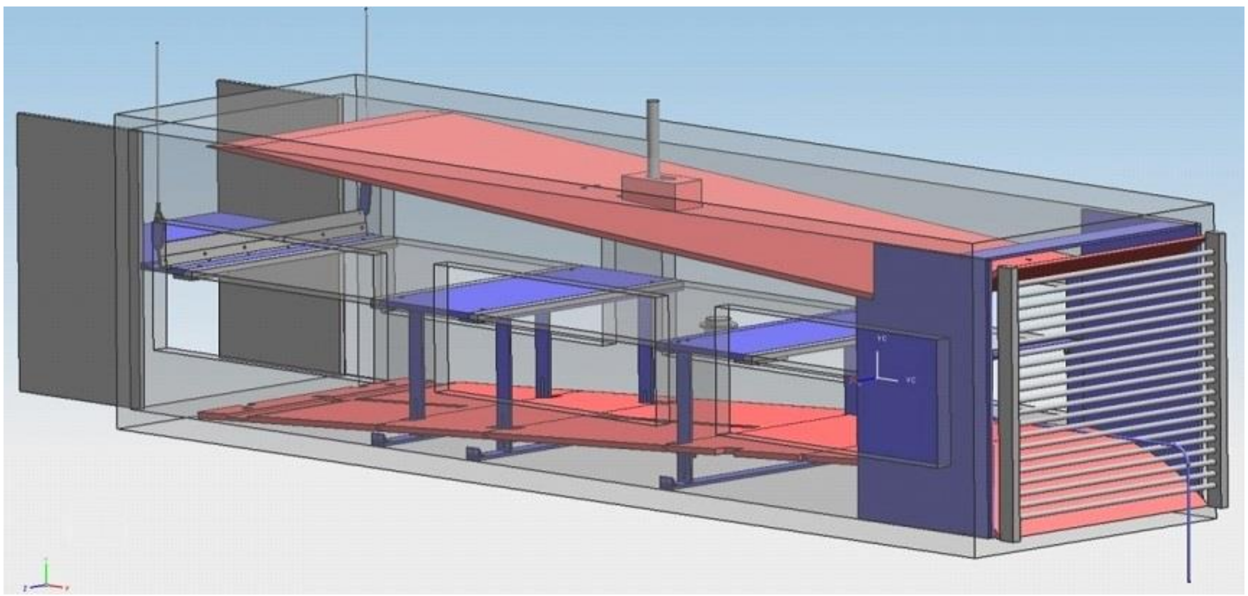

Figure 8. Schematic diagram of an experimental model within the MIR tunnel for adverse pressure gradients (flow is from right to left).[13]

[13] Skifton, R. 2015, *Entropy Generation for a Bypass Transitional Boundary Layer and Improved Particle Image Velocimetry Measurements Using the Particle Density Information,* PhD Dissertation, University of Idaho, Idaho Falls, ID.

[14] Kähler, C. J., S. Scharnowski, and C. Cierpka, 2012. On the resolution limit of digital particle image velocimetry. *Exp. Fluids*, 52, pp. 1629–1639.

[15] Kähler, C. J., S. Scharnowski, and C. Cierpka, 2012. On the uncertainty of digital PIV and PTV near walls. *Exp. Fluids*, 52, pp. 1641–1656.

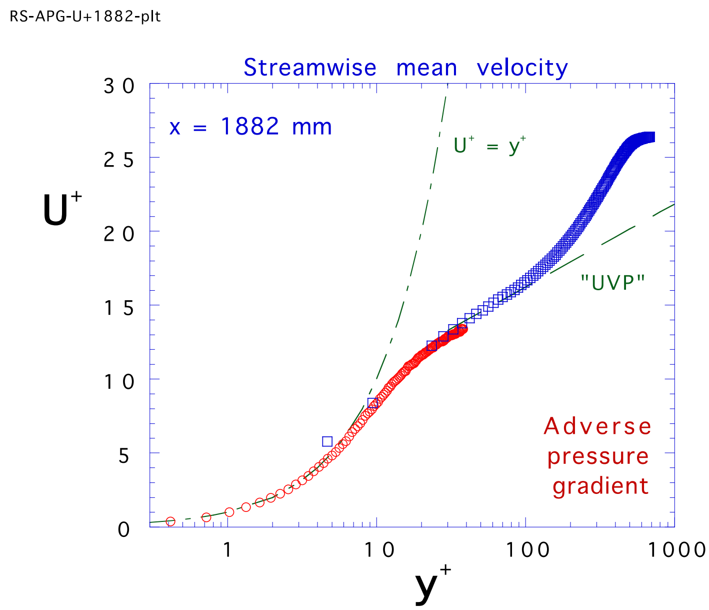

Figure 9. Streamwise mean velocity measurements by PTV and PIV in a developed turbulent boundary layer; circles = PTV from small FoV, squares = PIV from large FoV[16].

National and International Collaborations

Most studies in the MIR flow system have been done with international and/or national partners, and supported by a variety of sponsors. Examples include:

- Transition in boundary layers with the Lehrstuhl für Strömungsmechanik of Universität Erlangen, Germany[6]
- Flow phenomena in spent nuclear fuel canisters for the Department of Energy (DOE) Environmental Management Science program[7]
- Flow fields around buildings for assessment of computer simulations of fate and transport of airborne contaminants for Bechtel Research and Development Department[17]
- Effects of realistic surface roughness on turbomachinery flows with the University of Idaho for the Air Force Office of Scientific Research[11]
- Complex flows relating to advanced gas-cooled nuclear reactors for the DOE NERI (Nuclear Energy Research Initiative) program[18]

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16 Skifton, R., R. S. Budwig, D. M. McEligot, and J. C. Crepeau, 2013. Measurement of entropy generation within bypass transitional flow. Bull., Amer. Physical Soc., 58, No. 18, p. 466.

17 Knight, K. J., C. Barringer, J. M. Berkoe, G. E. McCreery, R. J. Pink, and D. M. McEligot, 2002. Physical and computational modeling for chemical and biological weapons airflow applications. Paper IMECE 2002-34451, ASME International Mechanical Engineering Congress and Exposition, New Orleans, November.

- Complex flows relating to supercritical water reactors for the DOE U.S./Korea I-NERI (International NERI) program[9]
- Synthetic jet actuators by the University of Wyoming for the Air Force Office of Scientific Research[19]
- Non-symmetrical swirling jet experiments by Utah State University for the DOE I-NERI program[20]
- Flow fields in the lower plena of gas-cooled reactors for the DOE Next-Generation Nuclear Plant program[21,22]
- Bypass flows in prismatic gas-cooled reactors with the University of Idaho for the DOE Next-Generation Nuclear Plant program[2]
- Entropy generation in bypass transition with University of Idaho for the DOE Office of Science.[13]

Availability of the MIR flow system has formed the basis for projects with international partners including Universität Erlangen, Universität Stuttgart, Universität der Bundeswehr München, Imperial College, Oxford University, University of Manchester, University of Montenegro, Kungliga Tekniska högskolan Stockholm, Kyoto University, University of Toyama, Seoul National University, and the Korea Advanced Institute of Science and Technology. These international projects have been summarized by McIlroy, Becker, and McEligot.[23] Most U.S. partners have been faculty and graduate students from universities including the University of Idaho, Boise State University, Utah State University, the University of Wyoming, Iowa State University, Johns Hopkins University, the University of Maryland, Ohio State University, and Pennsylvania State University. Some of these investigations are summarized by McIlroy and McEligot.[24] General Atomics, Bechtel, and Clarksean Associates have been industrial participants.

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18 McCreery, G. E., R. J. Pink, K. G. Condie, and D. M. McEligot, 2003. Fluid dynamics of ribbed annuli. Paper J00203, NuReTH-10, Seoul, October.

19 Shuster, J. M., R. J. Pink, D. M. McEligot, and D. R. Smith, 2005. The interaction of a circular synthetic jet with a cross-flow boundary layer. AIAA paper 2005-4749, AIAA Fluid Dynamics Conference, Toronto, June.

20 Wilson, B. M., B. L. Smith, R. E. Spall, and H. M. McIlroy, 2009. A non-symmetrical swirling jet as an example of a completely described assessment experiment. ASME paper FEDSM2009-78386.

21 McIlroy, H. M, D. M. McEligot, and R. J. Pink, 2010. Measurement of turbulent flow phenomena for the lower plenum of a prismatic gas-cooled reactor. *Nuc. Engr. Design*, 240. pp. 416–428.

22 McIlroy, H. M., D. M. McEligot, and R. J. Pink, 2010. Measurement of flow phenomena in a lower plenum model of a prismatic gas-cooled reactor. *J. Eng. Gas Turbines and Power*, 132 (2), pp. 022901-1–022901-7.

23 McIlroy, H. M., S. Becker, and D. M. McEligot, 2011. Large Matched-Index-of-Refraction (MIR) Flow Systems for Thermal Engineering Education. *Innovations 2011 World Innovations in Engineering Education and Research* (Ed.: W. Aung et al.), Potomac, Md.: International Network for Engineering Education and Research, Ch. 6, pp. 69–87.

24 McIlroy, H. M., and D. M. McEligot, 2011. The Idaho National Laboratory (INL) Matched-Index-of-Refraction (MIR) flow system. *J. Idaho Acad. Sci.,* 1 December.

Benefits

The MIR Facility enables optical measurements for determining flow characteristics in complex passages/geometries (such as turbomachinery passages, nuclear reactor tube bundles, nuclear reactor coolant channels, and boundary layers) in and around objects without distortion of optical paths. The MIR Facility is used as an informal user facility for basic and applied research by government, industry, and academia where accurate and reliable uncertainty quantification is essential for producing high-quality data for computer code validation, truly an international asset.

Acknowledgements

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